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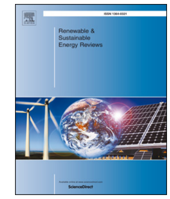

Integrated GHG emissions and emission relationships analysis through a disaggregated ecologically-extended input-output model; A case study for Saskatchewan, Canada

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ABSTRACT

Facing the potential conflict between economic and environmental challenges, it is essential to investigate the integrated GHG emissions and the emission relationships of all industries in a socio-economic system to support formulation of industrially related legislation. In this study, a disaggregated ecologically-extended input-output (DECEIO) model is developed to investigate integrated GHG emissions and the emission relationships of various industries. A special case study for the Province of Saskatchewan, Canada, is conducted to illustrate the potential benefits of its use in the formulation of industrially related legislation. A disaggregated analysis that contains three GHG types and four emission sources is conducted to gain more insight into the complicated interactions between different industries. It is found that all kinds of emission sources and GHG types should be considered to comprehensively identify the characteristics of emission flows in the socio-economic system. The competitive relationships reflect good interactions in the GHG emission flows and a mutualism relationship reveals effective pathways to mitigate carbon emissions in two sectors simultaneously. In the Province of Saskatchewan, the Agriculture and Forestry sector, Electric Power Generation, Transmission and Distribution sector, Construction sector and Household Consumption sector all rank at the top for GHG emissions and their relationships are mutualistic. Thus, it is vital to propose effective industrial legislation for these industries to realize GHG emission reduction targets.

1. Introduction

The release of greenhouse gases (GHG) and the resulting global climate change have gained considerable attention worldwide [1,2]. Many scientists believe that human activities are responsible for almost all of the increase in greenhouse gases in the atmosphere over the last 150 years [3,4]. Thus, all countries and jurisdictions are seeking GHG emission mitigation strategies to contribute climate-resilient pathways for sustainable development [5–8].

Economic production activity is an important direct and indirect source of GHG emissions. It is also a highly heterogeneous contributor that has different emission performances in various industrial sectors. Given the fact that the remaining potential for cost-effective emission reductions is still great, industrially related GHG legislation has been adopted in many regions all over the world, such as British Columbia [9], United States [10], and Europe [11]. Legislation for specific industries can effectively reduce the GHG emissions, but it may also increase the production costs and hinder economic development to different extents [12]. Economic activities are closely linked, with the legislation for one industry potentially affecting the economic activities of other industries. Thus, it is essential to reveal the integrated GHG emissions and emission relationships of all industries in a socio-economic system to support the formulation of industrial legislation.

Input-Output analysis (IOA) allows direct and indirect emissions by industry sector and final demand to be estimated at a disaggregated level [13]. Hence, IOA has been widely used in GHG emissions and emission intensity studies [14–18]. Different scopes of carbon footprint analysis were conducted for United States residential and commercial buildings through an input-output (I-O) hybrid life cycle assessment (LCA) approach [15]. Emissions from direct purchases of electricity

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were found to have the highest carbon footprint. Li et al., adopted a three-scale IOA to depict a specific urban economy's overall energy consumption impacted by local direct energy use, domestic and foreign trade, to establish a more reasonable energy conservation mechanism through both embodied energy and energy regulation scenario analyses [19]. A dynamic integrated I-O simulation model was constructed incorporating GHG emission intensities to explore potential pathways towards GHG emission peak prior to 2030 for China [20]. Schmidt et al. used environmentally-extended multi-regional IOA and the database EXIOBASE3 to compute Swedish consumption-based GHG emissions over a time period of 20 years [21]. Wang et al., developed a novel Chinese emission abatement sector extended I-O table through introducing abatement cost, emission charge and abatement benefit into the conventional I-O table, which was also applied to estimate the environmental efficiency and assess the effects of environmental policies on economy and environment [22]. As the second largest developing country and fourth largest carbon emitter in the world, India experienced increase of total carbon emissions and emission intensity during 2007–2013. The I-O framework was adopted to study India's total emissions and intensity changes and their driving forces with the latest data [23]. Su et al. comprehensively analyzed CO_2 emission intensities from a demand perspective using an I-O framework and investigated the drivers of emission changes using structural decomposition analysis [17]. An inter-region I-O table that included new sectors related to renewable energies was developed to effectively analyze the utilization of renewable energy facilities and design future smart energy systems in Japan [24].

Besides the research for a specific region, the integrated efficiency of inputs-outputs and unified performance in energy consumption and CO_2 emissions for the Chinese agricultural sector were explored to examine the reduction potential of energy intensity and CO_2 emission intensity [18]. Omidi-Arjenaki, Ebrahimi, and Ghanbarian investigated the input and output energy of honey production in Shahrekord to facilitate the economic analysis of honey production [25]. The construction sector delivers the infrastructure and buildings by consuming large amount of unrenewable energy, which causes the large emissions of CO_2. The level of CO_2 emission caused by the construction activities globally was explored and compared by using the world environmental I-O table [26]. Liu et al., presented an analysis of GHG emissions reduction in Chinese plastic recycling industries through an extended environmental I-O model. The trajectories, features, and driving forces of GHG emissions reduction achieved by the Chinese plastic recycling industries were revealed in this study [27]. The absence of process detail for sectors in I-O tables has been identified as a limitation of IOA in environmental-economic LCA [28]. Consumption-based material footprints calculated with IOA are influenced by the sectoral, spatial and material aggregations used in the I-O tables, and a lack of disaggregation can be a source of uncertainty [29,30]. The so-called aggregation bias problem should be addressed even if it is based on partial information to match the size of environmental satellite accounts, which will lead to smaller relative errors [31].

GHG emissions embodied in trade (EET) have an important and far-reaching impact on GHG emissions reduction obligations [32]. Thus, EET have also been widely studied in recent research. China's provincial CO_2 EET were analyzed through a Multi-Region Input-Output (MRIO) model, and several climate policy options that potentially reduce the impact of trade on individual provinces were discussed [32]. Both spatial and inter-sectoral linkages have been assessed to explore urban carbon transformations by means of a high-resolution MRIO model of Australia using Sydney and Melbourne as case studies [33]. Su and Ang studied the issue of imports assumption in embodied emission studies and found that the implications of the results obtained using different import assumptions are not identical [34]. Xu and Dietzenbacher quantified the driving forces behind the growth of carbon dioxide EET and suggested that policy makers should monitor EET more carefully and take the effects of trade on emissions into consideration [35]. Non-CO_2 emissions embodied in the international trade of meat, which includes beef, pork, and chicken produced in 237 countries over the period 1990–2010, were estimated to assess whether this activity tends to reduce or increase global emissions [36]. Henders, Persson and Kastner focused on the carbon emissions embodied in the production and exports of forest-risk commodities and analyzed the links between deforestation for four principal forest-risk commodities in seven high-deforestation countries and consumption through international trade [37]. Embodied emission flows between China and Japan were estimated using emissions embodied in a bilateral trade approach [38]. The results showed that technology effects contribute most to the decrease in embodied emissions.

When considering the complex interactions among various industries, the socio-economic system is similar to an ecological system. Different industries play different roles, such as producer, consumer, and decomposer. To reveal the inter-connections of different components, Ecological Network Analysis (ENA) has been adopted by many researchers in various fields. Chen and Chen applied ENA to determine which economic sector drives energy consumption and to what extent these sectors are dependent on each other for energy [39]. Zhang et al. adopted ENA for regional embodied energy accounting in China [40]. The results provide a basis for identifying how regional economic development policies influence embodied energy consumption and its flows between regions. ENA was also chosen as a useful tool to examine the structure and function of a virtual water network and the interactions among its sectors [41]. A Food Network Model from Guangdong perspective was developed based on both IOA and ENA. The proposed model was used to explore the nature of food flows in response to the regulation of sectoral activities [42]. ENA was adopted to establish a forest resource metabolism network model to tackle the increasingly scare forest resources. The results provided scientific reference to allocate forest resources and stabilize industrial structure [43]. The extended methods of network control analysis and network utility analysis were used in ENA to analyze industrial solid waste metabolism system [44]. Specially, virtual water flows within China's electric power system and the impact on water stress mitigation were analyzed [45]. In 2016, Wang and Chen proposed a ENA for the energy-water nexus and provided cross-cutting opportunities to mitigate urban energy and water demand pressure [46]. In soil ecology, ENA was used to investigate the biological diversity (i.e. soil microbial and faunal communities) associated with the major land use management types found across Europe and to examine how these various ecological networks relate to two key ecosystem services in the soil [47]. ENA also provided a powerful tool to analyze complex influences of social and ecological structures on community and household dynamics [48].

There has been increasing interests in GHG emissions through ENA. Xia et al., generated a spatial network model with 18 nodes consisting of natural and technical metabolic components and used ENA to quantitatively analyze the structure of the ecological relationships and summarize the key metabolic functions among different relationships of Beijing [49]. An information-based ENA was proposed to evaluate the distribution of embodied carbon flows in socio-economic networks. The proposed method was applied in China to examine the embodied carbon structure and production-based carbon intensity [50]. In order to reduce waste and pollution, share resources, and help with pursuit of sustainable development, eco-industrial parks were built to mitigate GHG emissions. Lu et al., developed a framework based on ENA to trace carbon metabolic processes in eco-industrial parks [51]. A multi-regional IOA and ENA were combined to assess carbon flows within China and identify key regions and sectors in the context of spatial heterogeneity for effective carbon mitigation [52]. Zhang et al. integrated multi-region IOA and ENA to analyze CO_2 emission flows, hotspots, divisions of labor, and directions of flows in the global production and consumption web. A plan to adjust current mitigation targets set by Paris Agreement was proposed based on the study results [53]. Besides, the coupling of energy and carbon flows were examined in some

previous studies. The interaction between urban carbon metabolism and socio-economic activities from a systems perspective was modeled based on a collection of system-based indicators from ENA [54]. Chen et al., developed a time-series dataset of carbon and energy flows and assessed correlations between energy consumptions and carbon emissions with consideration of urban size and population density [55].

However, there have been very limited studies on disaggregated GHG emission relationships in a socio-economic system, which is a key issue to support the formulation of industrial legislation. Furthermore, previous studies on GHG emissions and EET focused on combustion-related GHG emissions, while emissions from other sources were neglected. For an economy that relies on agriculture and raw resource extraction, GHG emissions from enteric fermentation and GHG leaking also accounts for a relatively large proportion of total emissions. Additionally, the GHG types (i.e. CO_2, CH_4, and N_2O) and GHG emission sources (i.e. gas, oil, coal, and other) all have significant impact on different industries' integrated GHG performances. The emission relationships of various industries will also change along with the GHG types and sources. Therefore, a disaggregated GHG emissions and emission relationships analysis is desired.

The objective of this paper is to develop a disaggregated ecologically-extended input-output (DECEIO) model that facilitates an integrated GHG emission and emission relationships analysis for different countries, provinces, and regions. The developed model will be applied to a detailed case study of the Province of Saskatchewan, Canada, to illustrate the potential benefits on industrial legislation formulation. More specifically, the DECEIO model will be developed based on IOA and ENA. The I-O table will be transformed and disaggregated based on the energy use patterns and economic structure within the Province of Saskatchewan. Direct and indirect GHG emissions of thirteen sectors will be first calculated. Emission embodied in exports (EEE), emissions embodied in imports (EEI), and emissions embodied in trade balances (EEB) will be estimated to investigate the impacts of potential regulations on imports and exports. Emission relationships of various industries will be revealed to explore the effective pathways to mitigate the GHG emissions of two sectors simultaneously. A disaggregated analysis, which enables three GHG types and four GHG emission sources, will be conducted to gain more insight into the system and facilitate more concrete policy-making. The results will provide a detailed scientific basis for supporting the formulation of effective industrial legislation under both economic and environmental challenges.

2. Methods

2.1. Disaggregated Ecologically-extended Input-Output model

A DECEIO model is developed to facilitate the analysis of integrated GHG emissions and emission relationships of different industries, which will further support industrial legislation formulation for different areas. Based on the concepts of flow-based network analysis, the direct emission flows among all the components in the socio-economic system are first obtained through the I-O table and the direct emissions to the environment of different sectors. The I-O table has been aggregated and disaggregated to match the environmental satellite accounts. Following this, the indirect emissions, EEE, EEI, and EEB are calculated to identify the characteristics of a system. Next, the integral utility matrix is computed to reveal the emission relationships between pairs of sectors. The developed DECEIO model can be applied in any country, province, and/or region with the following descriptions.

The DECEIO model is based on the Leontief framework [13]. In this section, we first outline the I-O Leontief framework. Consider an economy with N sectors where each sector i produces a unique good. The total output of sector i is the sum of the intermediate consumption by the economy and the final demand [13,28,56].

$$x_i = \sum_{j=1}^{N} z_{ij} + f_i \quad \text{for } i = 1 \text{ to } N \tag{1}$$

where x_i is the total output of *ith* sector, z_{ij} is the amount of good i that sector j consumes, f_i is the final demand of *ith* sector.

In the I-O Leontief framework, it is assumed that industry flow from sector i to sector j depends linearly on the total output of sector j [13]. Eq. (1) can be rewritten as:

$$x_i = \sum_{j=1}^{N} a_{ij}x_j + f_i \quad \text{for } i = 1 \text{ to } N \tag{2}$$

where a_{ij} is the units of good i to produce 1 unit of good j.

Considering the system with α GHG emission sources and β GHG emission types, $(\alpha + 1) \times (\beta + 1)$ scenarios are conducted to reflect the differences among industrial emission performance, including total GHG emissions from all sources, GHG emissions from α sources, β emissions from all sources, and $\alpha \times \beta$ combination scenarios. In each scenario, the direct emissions $\mathbf{E}_k$, which is the direct emissions of thirteen sectors, are used to obtain the emission flows among different sectors in the entire system, as shown in Eq. (3):

$$\mathbf{E}_k + \varepsilon_k\mathbf{Z} = \varepsilon_k\mathbf{X} \quad for \ k = 1 \ to \ (\alpha + 1) \times (\beta + 1) \tag{3}$$

where ε_k represents the embodied emission coefficient matrix of *kth* emission and $\mathbf{Z}$ represents the value flow matrix in the I-O table. $\mathbf{X} = [x_{ij}]_{N\times N}$, when $i = j$ and $u_{ij} = x_i$, when $i \neq j$ and $u_{ij} = 0$.

Eq. (3) can be rewritten as:

$$\varepsilon_k = \mathbf{E}_k[\mathbf{X} - \mathbf{Z}]^{-1} \tag{4}$$

Next, using the embodied emission coefficient matrix ε_k, the emission flows in the network can be obtained. In this single-region I-O model, non-competitive imports assumption is adopted [34]. The emission flows $\mathbf{IE}_k$, emissions embodied in exports $\mathbf{EEE}_k$, emissions embodied in imports $\mathbf{EEI}_k$, and emissions embodied in trade balances $\mathbf{EEB}_k$ can be calculated by Eqs. (5)–(8):

$$\mathbf{IE}_k = \varepsilon_k\mathbf{Z} \tag{5}$$

$$\mathbf{EEE}_k = \varepsilon_k\mathbf{X}^e \tag{6}$$

$$\mathbf{EEI}_k = \varepsilon_k\mathbf{X}^i \tag{7}$$

$$\mathbf{EEB}_k = \varepsilon_k\mathbf{X}^e - \varepsilon_k\mathbf{X}^i \tag{8}$$

where $\mathbf{X}^e$ represents the export matrix in the I-O table and $\mathbf{X}^i$ represents the import matrix in the I-O table.

In the emission flow matrix, the elements IE_{ij} represent the direct flows from sector i to sector j. Thus, the total emissions T_i that flow into sector i from other sectors and system boundaries can be calculated using Eq. (9).

$$T_i = \sum_j IE_{ij} + E_i \tag{9}$$

The direct utility matrix $\mathbf{D}$ and integral utility matrix $\mathbf{U}$ are then computed to reveal the mutual relationships between pairs of sectors by Eq. (10) and Eq. (11) [57–59].

$$d_{ij} = \frac{(IE_{ij} - IE_{ji})}{T_i} \tag{10}$$

$$\mathbf{U} = [u_{ij}] = \mathbf{D}^0 + \mathbf{D}^1 + \mathbf{D}^2 + \ldots + \mathbf{D}^k + \ldots = (\mathbf{I} - \mathbf{D})^{-1} \tag{11}$$

where $\mathbf{D}$ represents a matrix of emission flows of a given path length, and the superscript following $\mathbf{D}$ (which ranges from 0 to maximum possible length) indicates the path length. $\mathbf{I}$ is the identity matrix of size $N \times N$.

Since the integral utility matrix reflects the overall relationships between various sectors, the positive and negative signs of the elements in $\mathbf{U}$ are used to judge the nature of the inter-relationships between pairs of sectors. According to the ecological relationships, five types of

emission relationships are considered in our analysis: (+, -) stands for exploitation, (-, +) stands for control, (0, 0) stands for neutralism, (-, −) stands for competition, and (+, +) stands for mutualism. Among them, exploitation and control are reciprocal relationships, and these two relationships are combined into one type (i.e. exploitation) in this study.

2.2. Data sources and scenarios

The two main inputs of the DECEIO model are I-O tables and the direct emissions of different sectors. The developed DECEIO model can be applied to any area when the above two inputs are obtained. In this study, the DECEIO model is applied to the Province of Saskatchewan to illustrate the potential benefits of the developed model on industrial legislation formulation. In addition, Saskatchewan is facing significant GHG emission reduction challenges after the Paris Agreement. It is thus desirable to conduct the integrated GHG emissions and emission relationships analysis to find out the most economic efficient pathways.

The input-output table of Saskatchewan has been aggregated and disaggregated based on data availability and sector characteristics following Wolsky [60] and Marriot [61]. For example, the "mining, quarrying, and oil and gas extraction" sector has been disaggregated into four sectors, including "crude oil extraction", "natural gas extraction", "coal mining" and "other mining and quarrying". The final I-O table used in this study contains thirteen sectors, as listed in Table 1. Particularly, household consumption is also considered as a sector in the emission network, since household consumption emits considerable GHGs into the system and is closely related with industrial sectors. The detailed aggregation and disaggregation process is described in another study by Liu et al. [62]. The direct emissions of different sectors were taken from Statistics Canada [63], NIR [64], ECCC [65], and other references.

Taking the three GHG types (i.e. CO_2, CH_4, and N_2O) and four emission sources (i.e. gas, oil, coal, and other) into consideration, twenty scenarios are built and analyzed, including total GHG from all sources, total emissions of three types of GHG from all sources, total GHG emissions from four sources, and twelve combination scenarios. The direct and indirect emissions, EET, and emission relationships under twenty scenarios are conducted separately to facilitate the detailed comparison analysis, which will provide more insights into the entire system.

3. Result analysis

3.1. Direct and indirect emissions

Using the methods developed in this study, the direct emissions and indirect emissions of three GHGs (i.e. CO_2, CH_4, and N_2O) from four sources (i.e. gas, oil, coal, and other) for thirteen sectors are calculated, as shown in Fig. 1 and Fig. 2.

The total GHG emissions of all sectors in the Province of Saskatchewan is 251.9 Mt, with the direct and indirect GHG emissions being 74.8 Mt and 177.1 Mt respectively. The indirect emissions are 2.4 times the direct emissions, which shows the significance of indirect emissions. According to Fig. 1(a), the total GHG emissions of Services sector is the highest, followed by the Household Consumption sector, Agriculture and Forestry sector, and Crude Oil Extraction sector. In the contrast, the total GHG emissions of Coal Mining sector is relatively low, as well as the Natural Gas Extraction sector, and Other Manufacturing sector. When only considering direct emissions, the GHG emissions of Crude Oil Extraction sector, Agriculture and Forestry sector, and Electric Power Generation, Transmission and Distribution sector rank at the top, which has relatively low indirect emissions. It is worth noting that a majority of GHG emissions of Services sector are indirect emissions, which contribute 96% of its total GHG emissions. Household Consumption sector has the next highest indirect GHG emissions. These sectors can be classified into two categories based on their total GHG emission performance. Five sectors emit more direct GHG emissions, including the Agriculture and Forestry sector, Crude Oil Extraction sector, Natural Gas Extraction sector, Electric Power Generation, Transmission and Distribution sector, and Transportation and Warehousing sector. The other eight sectors emit more indirect GHG emissions, which is closely correlated to their industrial characteristics and production structures. In other words, production activities for a primary industry are more likely result in direct GHG emissions, while indirect GHG emissions are most likely to happen in secondary and tertiary industries.

When comparing the three different kinds of GHGs, it can be seen from Fig. 1(b), (c), and (d) that CO_2 accounts for a large proportion of the total GHG emissions. The total CO_2, CH_4, and N_2O emissions are 187.1 Mt, 39.5 Mt, and 24.1 Mt respectively. Upon further investigation, Fig. 1(c) shows that the CO_2 emission performances of most sectors is similar to the GHG emission performances, except for the Agriculture and Forestry sector and Crude Oil Extraction sector. The direct CO_2 emissions in the Agriculture and Forestry sector is decreased, while the indirect CO_2 emissions in the Agriculture and Forestry sector is increased. In Fig. 1(b) and (d), the ratio of indirect and direct emissions is decreased, especially for CH_4 emissions (i.e. 1.06). The highest CH_4 emission sector is the Crude Oil Extraction sector and the highest N_2O emission sector is the Agriculture and Forestry sector, which are totally different in comparison with CO_2 emissions. It is also worth noting that the direct N_2O emissions in the Agriculture and Forestry sector is 94% of the total direct N_2O emissions, indicating that Agriculture and Forestry sector is the key sector for reducing N_2O emissions.

A significant variance is also observed in comparison among four emission sources, as shown in Fig. 1(e), (f), (g), and (h). In each scenario, Services sector and Household Consumption sector rank at the top for total GHG emissions, most of which are indirect GHG emissions. The total GHGs from gas are most nearly occurring in the Services sector, Household Consumption sector, and Crude Oil Extraction sector, while the direct GHGs from gas are most significantly observed in the Crude Oil Extraction sector. Agriculture and Forestry sector and Transportation and Warehousing sector contribute over 62% of the total direct GHG emissions from oil. The Agriculture and Forestry sector and Crude Oil Extraction sector also emit most of the GHGs from other sources. For the GHG emissions from coal, almost all of them are come from the Electric Power Generation, Transmission and Distribution sector, which shows that only coal is used for electric power generation in Saskatchewan. According to the National Energy Board, coal and coke power generation accounts for forty-nine percent of the total generation in 2016. In contrast, only seventeen percent of the electric power was produced from renewable energy [66]. To realize the GHG emission reduction target, the utilization of renewable energy should be improved, including hydro, wind, and biomass. In addition, the total GHG emissions from the four sources have little differences, illustrating

Table 1
Sector definition.

Abbreviation	Sector
AGR	Agriculture and Forestry
MIN	Other Mining and Quarrying
COL	Coal Mining
GAS	Natural Gas Extraction
CRU	Crude Oil Extraction
OIL	Petroleum and Coal Products Manufacturing
ELE	Electric Power Generation, Transmission and Distribution
CON	Construction
MFR	Other Manufacturing
TRN	Transportation and Warehousing
TRD	Wholesale Trade and Retail Trade
SER	Services
C	Household Consumption

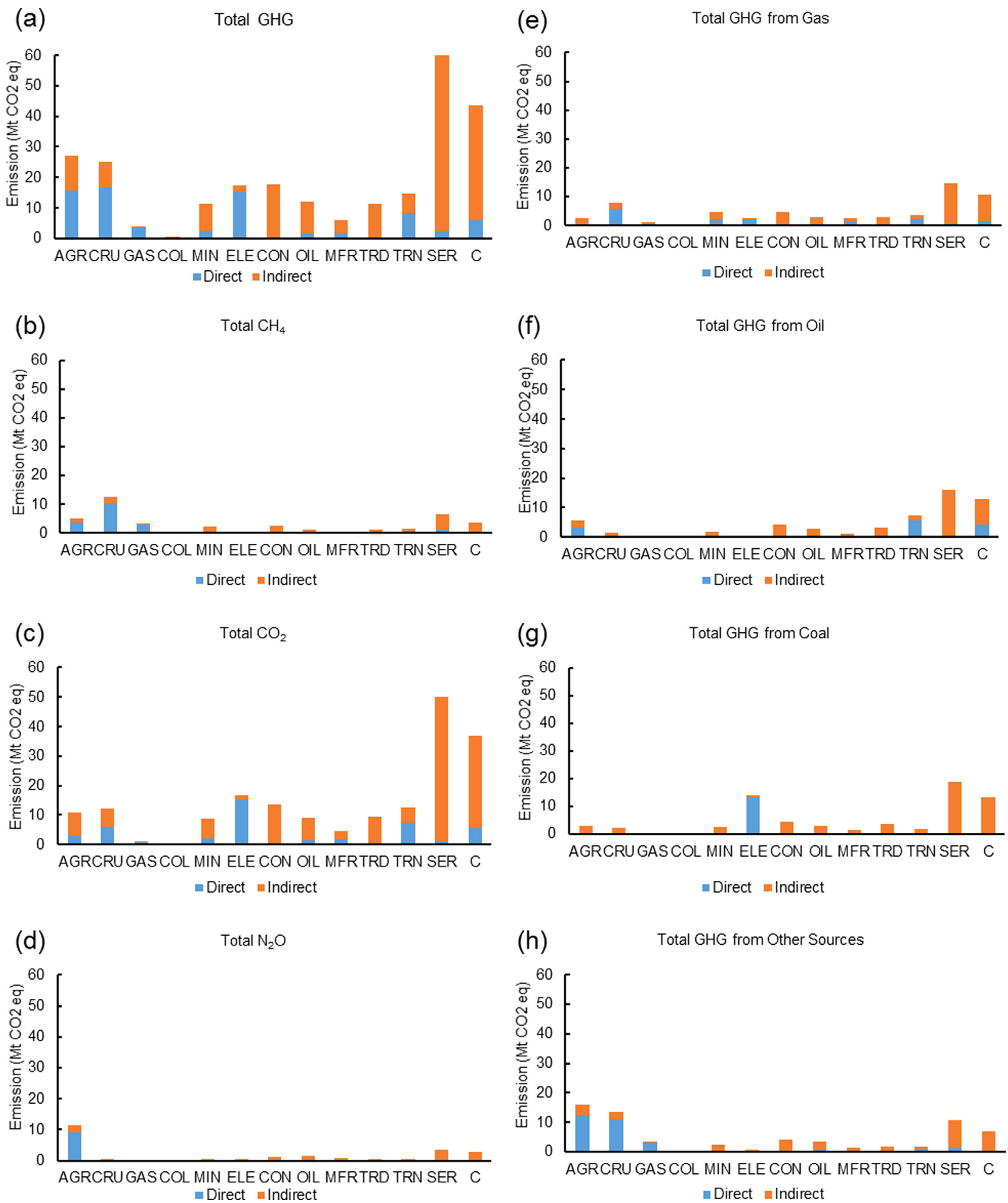

Fig. 1. Direct and indirect emissions of thirteen sectors.

that all kinds of emission sources should be considered to comprehensively identify the characteristics of the socio-economic system.

To further investigate the interactive relationships of GHG types and emission sources, twelve combination scenarios are conducted, as shown in Fig. 2. By comparing the three columns, it can be seen that CH_4 emissions are mainly caused by gas utilization and other sources, and N_2O emissions almost all come from other sources. The CO_2 emissions, which account for a large proportion of the GHG emissions, are mainly caused due to the utilization of fossil fuels, including natural gas, oil, and coal. There is no doubt that other sources, which contain biomass, ethanol, landfill gases/waste, steam and process emissions, produce CH_4 and N_2O during their utilization processes. As the cleanest fossil fuel, natural gas utilization in the Agriculture and Forestry sector, Crude Oil Extraction sector, and Natural Gas Extraction sector emits considerable CH_4 directly, which shows that the combustion of natural gas in these industries is not complete. This further indicates that

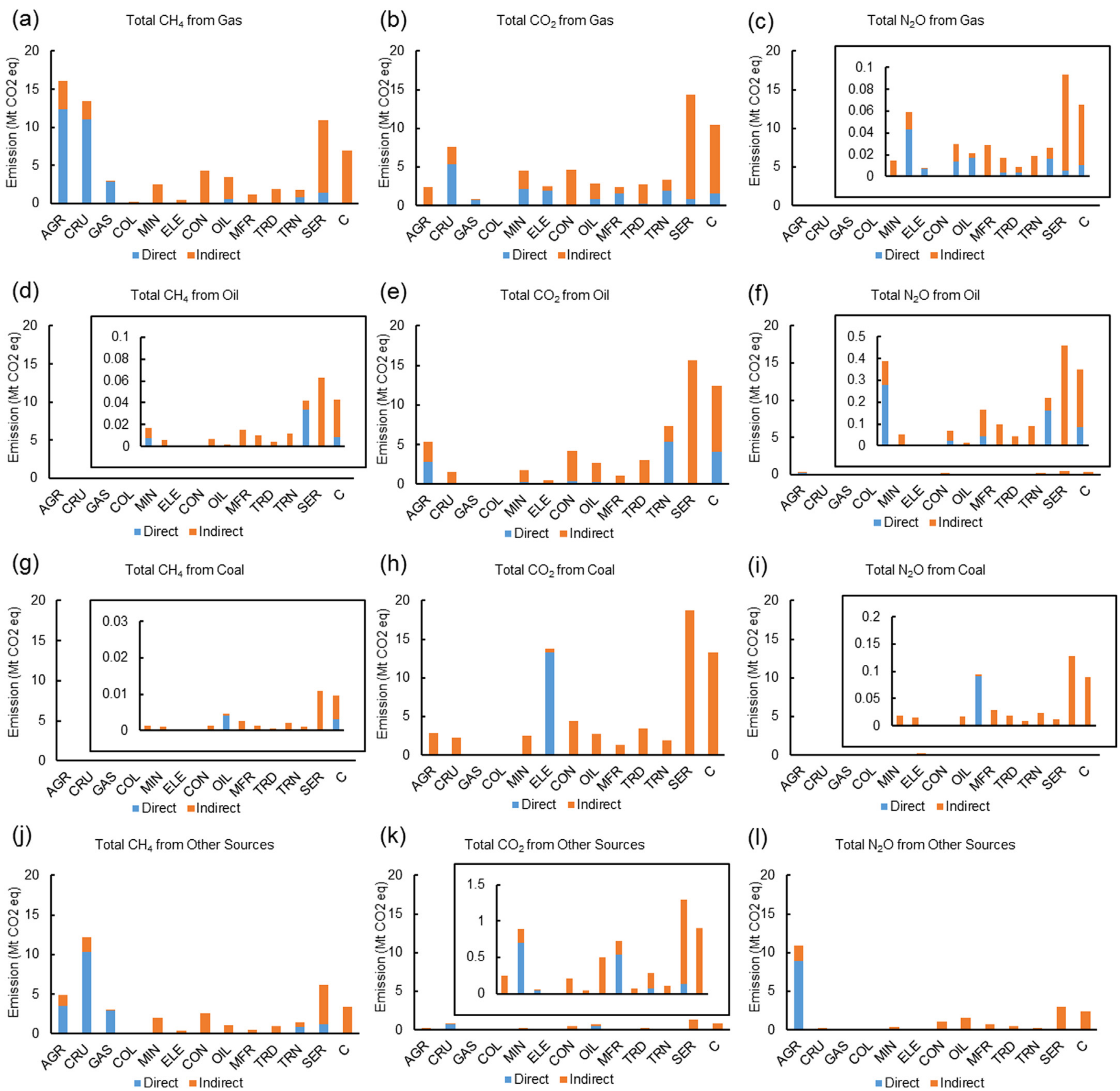

Fig. 2. Disaggregated direct and indirect emissions of thirteen sectors.

technologies in the above industries should be improved to reduce GHG emissions.

Overall, the direct and indirect emission analysis is essential to support industrial GHG emission reduction policy-making. For industries that result in direct emissions (i.e. Agriculture and Forestry sector, Crude Oil Extraction sector, and Electric Power Generation, Transmission and Distribution sector), the focus should be on production-based regulations. In contrast, consumption-based regulations should be considered for those industries that cause indirect emissions (i.e. Services sector, Construction sector, and Household Consumption sector). In addition, some particular phenomena can be observed through the disaggregation analysis. The CH_4 emissions account for a great proportion of the total GHG emissions in the Crude Oil Extraction sector. According to the actual production condition, venting and fugitive CH_4 emissions are hard to be regulated and reduced. Thus, regulations on flaring CH_4 emissions in the Crude Oil Extraction sector should be addressed. Clean coal-fired electric power generation and renewable energy power generation are the key issues to reduce the CO_2 emissions from coal, since 99% of CO_2 emissions from coal occur in the Electric Power Generation, Transmission and Distribution sector. The Province of Saskatchewan has made significant efforts in cutting-edge energy storage technologies, which will help to meet the ups and downs of electricity demand and maximize the benefits of these renewable sources. In addition, electricity grid modernization is also required to integrate more renewable energy into the entire electric power system. Agriculture and Forestry sector is a key industry in Saskatchewan, but its emission ranks at the top for both CH_4 and N_2O. Besides enteric fermentation, manure management, field burning of crop residues, and other emissions from other sources, it can be seen that Agriculture and Forestry sector emits considerable CH_4 due to the

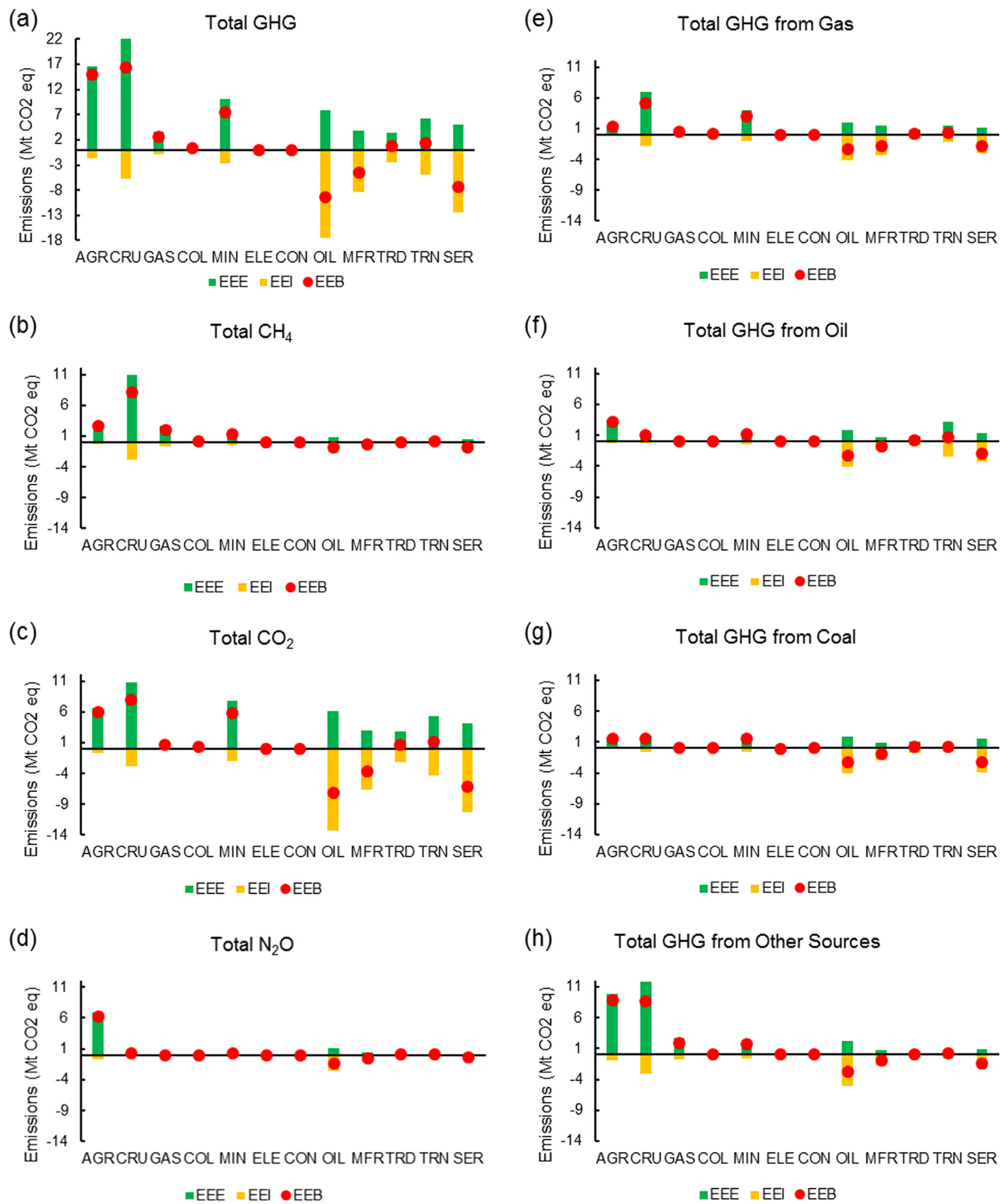

Fig. 3. Emission embodied in trade between twelve sectors.

utilization of natural gas. Thus, clean natural gas combustion and renewable energy utilization technologies should be applied in the Agriculture and Forestry sector. Organic material such as solid wood or wood residues, agricultural crop residues and animal wastes can be directly used as biomass to generate power. In Saskatchewan, biomass power generation only accounts for three percent of the total power generation capacity. Considering the abundant agricultural resources, biomass utilization should be emphasized in the future, especially for the Agriculture and Forestry sector.

3.2. Emissions embodied in trade

National and international total GHG emissions embodied in trade have been found to be increasing. Therefore, the EEE, EEI, and EEB of

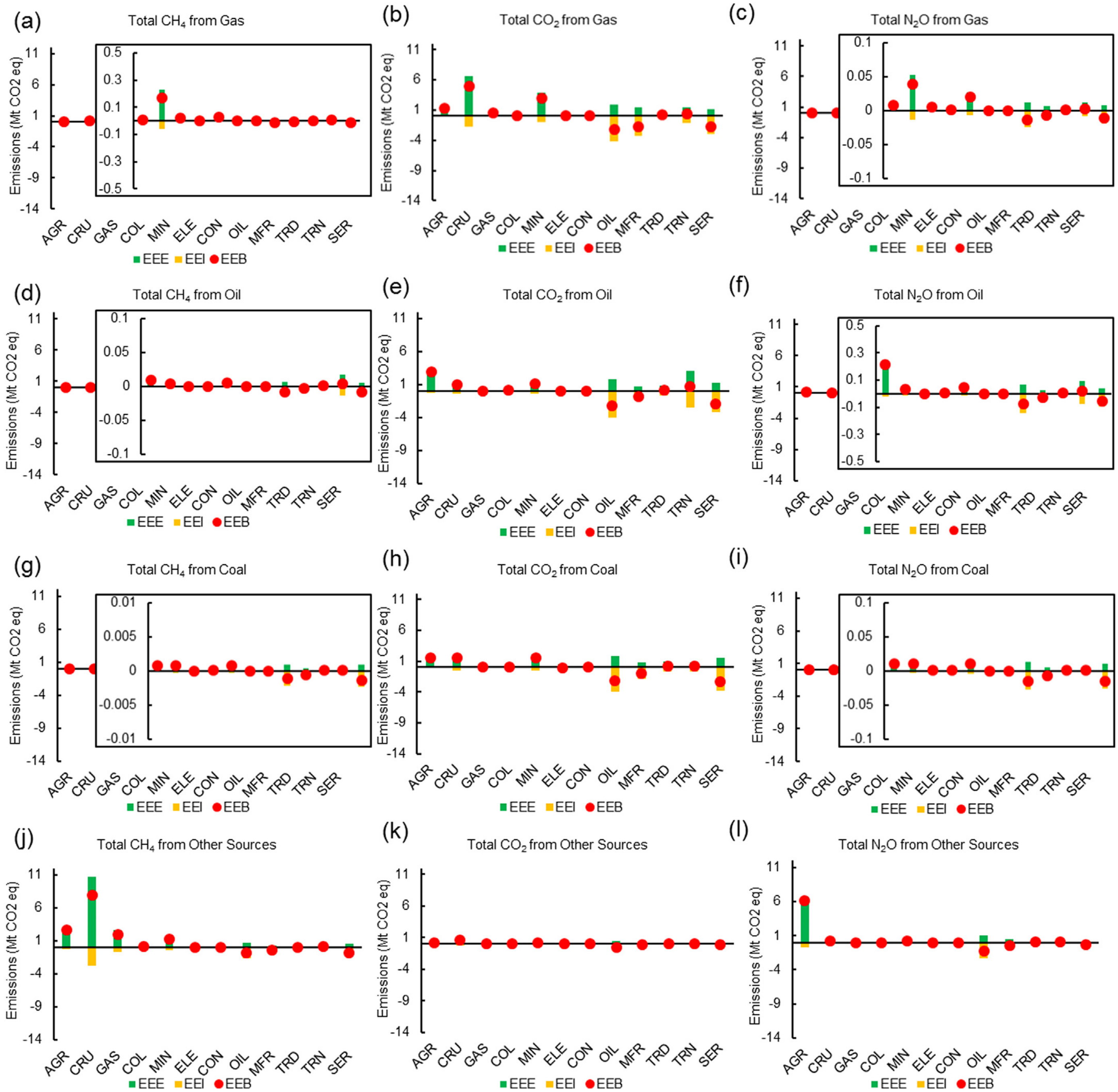

Fig. 4. Disaggregated emissions embodied in trade of twelve sectors.

three GHGs (i.e. CO_2, CH_4, and N_2O) from four sources (i.e. gas, oil, coal, and other) for twelve industrial sectors were calculated, as shown in Fig. 3 and Fig. 4.

The total GHG EEB of all sectors in the Province of Saskatchewan is 22.2 Mt, with the total for EEE and EEI being 79.8 Mt and −57.6 Mt respectively. This finding shows that the net EET of Saskatchewan is exported to other regions, which further indicates that a consumption-based emission reduction responsibility system will benefit the province. It can be seen in Fig. 3 that most industries have emissions embodied in trade and their performance varies significantly. There are five industries that have higher EEE than EEI, including Agriculture and Forestry sector, Crude Oil Extraction sector, Natural Gas Extraction sector, Other Mining and Quarrying sector, and Transportation and Warehousing sector. While, the Petroleum and Coal Products Manufacturing sector, Other Manufacturing sector, and Services sector have net emissions embodied in their imports. The EEB of the other four industries (i.e. Coal Mining sector, Electric Power Generation, Transmission and Distribution sector, Construction sector, and Wholesale Trade and Retail Trade sector) tend to be zero. Among them, the Coal Mining sector, Electric Power Generation, Transmission and Distribution sector, and Construction sector have both relatively small EEE and EEI, which shows that the economic activities of these industries mostly happen in the province. In contrast, the EEB and EEI of Wholesale Trade and Retail Trade sector is much higher, indicating that various trade activities happen between Saskatchewan and other jurisdictions. It's worth noting that the EEE of Crude Oil Extraction sector, Agriculture and Forestry sector, and Other Mining and Quarrying sector is significant, which is consistent with real conditions. This result further

indicates that emission reduction regulations on the Crude Oil Extraction sector, Agriculture and Forestry sector, and Other Mining and Quarrying sector will have significant impacts on the economy, since the cost increase will reduce their competitiveness in the national or international commodity market.

As shown in Fig. 3(b), (c), and (d), the EET of three different kinds of GHGs varies considerably. In each scenario, a significant variance is also observed in comparison to different industries. When focusing on the CO_2 EET, it can be seen in Fig. 3(c) that most industries have the same trends with Fig. 3(a). The biggest difference is that the ratio of EEE in the Natural Gas Extraction sector is decreased. Meanwhile, an increase of the ratio of EEE in the Natural Gas Extraction sector is observed in Fig. 3(b), indicating that most of the GHG EET of the Natural Gas Extraction sector is CH_4 emissions. The N_2O EET of most industries are relatively low, except the Agriculture and Forestry sector. This result is mainly caused by the low N_2O emissions, as shown in Fig. 1(d). It is worth noting that the majority of EET in the Agriculture and Forestry sector is CO_2 and N_2O, while CH_4 and N_2O account for a large proportion of emissions embodied in the trade of the Crude Oil Extraction sector. In addition, the CO_2 EET of the Other Mining and Quarrying sector is relatively significant, considering its low emissions. The same phenomenon can be seen in the Petroleum and Coal Products Manufacturing sector. These results indicate that there are abundant import and export activities that are emission-intensive in the Other Mining and Quarrying sector and Petroleum and Coal Products Manufacturing sector in Saskatchewan.

When comparing the four emission sources, it can be seen in Fig. 3(e), (f), (g) and (h) that GHG emissions from other sources are the largest emissions embodied in trade. The total GHG EEB from gas, oil, coal, and other are 4.6 Mt, 1.3 Mt, −0.3 Mt, 16.6 Mt respectively. In comparison with Fig. 1(e), (f), (g) and (h), the results show that the EET performance is totally different from the emission performance. Thus, it is important to analyze both performances. Upon further investigation, Fig. 3(h) shows that the Agriculture and Forestry sector and Crude Oil Extraction sector have large GHG EEE from other sources. Besides having GHG EET from other sources, the Crude Oil Extraction sector industry exports high GHG emissions from gas and the Agriculture and Forestry sector exports relatively high GHG emissions from oil. Moreover, the GHG EET of the Other Mining and Quarrying sector is significant in emanating from four emission sources. Among them, the EET from gas (i.e. EEE = 4, EEI = -1.1, EEB = 2.9) is larger than the EET from other sources, indicating that EET in the Other Mining and Quarrying sector industry are most caused by gas utilization and most of them are exported to other areas. The total GHG EET of other industries are almost evenly distributed across the four emission sources, which is totally different from their emission performance. This result shows that the EET of most industries are not bound up with their emission source, except those from export based emission-intensive industries (i.e. Agriculture and Forestry sector, Crude Oil Extraction sector, and Other Mining and Quarrying sector).

Fig. 4 shows the EET performance of various industries under twelve combination scenarios of GHG types and emission sources. By comparing the three columns, it can be seen that CH_4 and N_2O EET generally come from other sources. Particularly, the N_2O EEE of the Agriculture and Forestry sector is 6.7 Mt, which is 75% of the direct N_2O emissions in the Agriculture and Forestry sector. The CH_4 EEE of the Crude Oil Extraction sector is 10.7 Mt, which accounts for 98% of the total CH_4 EEE of the Crude Oil Extraction sector. It can be seen in Fig. 4(b), (e), (h) and (k) that the CO_2 EET are more complex, with the net EEB of four emission sources being 4.4 Mt, 1.2 Mt, −0.3 Mt, 0.1 Mt respectively. Among them, the EEI of total CO_2 EET from coal is the largest, resulting in a negative net EEB. For the CO_2 EET from gas, even though the EEI in the Petroleum and Coal Products Manufacturing sector is almost the same value, the EEE of the Crude Oil Extraction sector and Other Mining and Quarrying sector are much higher, leading to a positive net EEB.

To sum up, the EET performances of various industries are substantially different with their emission performances. Compared to the emission sources, GHG emissions are more closely related with their industrial emission performances. The EET of most industries are not bound up with their emission sources, except those from export based emission-intensive industries (i.e. Agriculture and Forestry sector, Crude Oil Extraction sector, and Other Mining and Quarrying sector). The net EET of Saskatchewan is exported to other regions, indicating that a consumption-based emission reduction responsibility system will benefit the province. Emission reduction regulations on the Crude Oil Extraction sector, Agriculture and Forestry sector, and Other Mining and Quarrying sector will have significant impacts on Saskatchewan's economy, since the cost increase will reduce their competitiveness in the national or international commodity market. Therefore, supportive policies, such as government investment and clean technology funding, are suggested to reduce the economic risks by reducing GHG emissions, especially for industries with net positive EEB.

3.3. Emission relationships

There are compounded interactions amongst various components in the socio-economic system. The relationships among different sectors are complicated regarding to their emission performance. A total of 91 pairs of emission relationships across thirteen sectors under twenty scenarios were analyzed, as shown in Table 2 and Fig. 5.

According to Fig. 5, the emission relationships of different sectors vary significantly, since the colors of different grids have large differences. The warm colors represent positive values and the cold colors represent negative values. By combining the two grids that are symmetric around the diagonal line, the emission relationship of two sectors can be determined. The color shade of one certain grid changes under different scenarios, and some even change to opposite colors in special scenarios. In a comparison of the twenty scenarios, it can be found that the emission relationships of two certain sectors will change. Table 2 shows the numbers of four emission relationships, including mutualism, competition, exploitation, and neutralism. No neutralism relationship is observed in the table, indicating that the all sectors are strongly associated with each other. Exploitation relationships account for a large proportion of all scenarios. Competition relationships are less than 16% for most of the scenarios, and some are even lower. Mutualism relationships account for 15–28% of the total relationships, which indicates a need to improve the overall system.

In ecological systems, consumers exploit producers and primary consumers are controlled by secondary consumers. By changing the system to a socio-economic system, different conclusions can be generated. Table 3 shows the emission relationships in scenario (t), which takes all GHGs and all emission sources into consideration. It can be seen that the entire system is dominated by exploitation relationships. As the exploiter, one sector obtains positive effects from other sectors and it is controlled by other sectors. Through the emission relationship analysis, exploiter can trace its emission source, and further adjust its production structure to achieve the emission reduction goal. As the exploitee, one sector transfers more GHG emissions to other sectors. Such sectors should improve the production technology to reduce their emission intensity, which will further help to realize the total GHG emissions in the system. For example, the emission relationship of the Agriculture and Forestry sector and the Other Manufacturing sector is (-, +), indicating that the Agriculture and Forestry sector obtains a net negative utility from Other Manufacturing sector and Other Manufacturing sector receives a positive utility from the Agriculture and Forestry sector. There are three sectors that exploited by most of other sectors, including Electric Power Generation, Transmission and Distribution sector, Transportation and Warehousing sector, and Household Consumption sector. In contrast, the Other Mining and Quarrying sector, Coal Mining sector, Crude Oil Extraction sector, and Construction sector play an exploitative trend towards a majority of other

Table 2
The numbers for emission relationships of each scenario.

Scenario			Emission relationships			
Numbering	Emission type	Emission source	Mutualism	Exploitation	Competition	Neutralism
a	CH_4	Gas	15	55	21	0
b	CO_2	Gas	16	59	16	0
c	N_2O	Gas	16	61	14	0
d	GHG	Gas	16	58	17	0
e	CH_4	Oil	16	63	12	0
f	CO_2	Oil	17	62	12	0
g	N_2O	Oil	21	68	2	0
h	GHG	Oil	17	62	12	0
i	CH_4	Coal	14	62	15	0
j	CO_2	Coal	14	63	14	0
k	N_2O	Coal	14	63	14	0
l	GHG	Coal	14	63	14	0
m	CH_4	Other	16	58	17	0
n	CO_2	Other	14	54	23	0
o	N_2O	Other	26	52	13	0
p	GHG	Other	18	57	16	0
q	CH_4	All	16	58	17	0
r	CO_2	All	15	67	9	0
s	N_2O	All	22	61	8	0
t	GHG	All	17	63	11	0

sectors. For instance, it can be seen in the Construction sector column of Fig. 5(t) that nine grids in this column are warm colors, indicating that it exploits nine sectors in the whole system. In the socio-economic system, the Construction sector and Household Consumption sector are considered as the highest consumers. However, their emission relationships with other sectors are totally different. These results show that the emission relationships of various sectors are not all consistent with the economic structure. Also, this may differ in different jurisdictions. Thus, GHG emission reduction regulations for specific industries should be on the strength of a scientific emissions relationship analysis.

The colors of the grids in the diagonal line are all white, indicating that the internal flows in a sector always benefits itself. Besides these thirteen grids, there are only four mutualism relationships (i.e. (Agriculture and Forestry sector, Construction sector), (Agriculture and Forestry sector, Household Consumption sector), (Construction sector, Electric Power Generation, Transmission and Distribution sector) and (Construction sector, Transportation and Warehousing sector)). In a mutualism relationship, both sectors benefit from the interactive flows, which is beneficial for the entire system. The mutualism relationship is more meaningful in an emissions relationship, since it reveals effective pathways to mitigate GHG emissions. For instance, the GHG emissions of the Construction sector will decrease once the emissions of the Electric Power Generation, Transmission and Distribution sector are decreased due to their positively related emissions relationship. Therefore, the emissions reduction in one sector will lead to a decrease of the total GHG emissions in other sectors that have a mutualism emissions relationship with. Transport energy use is growing rapidly, leading to an increase in GHG emissions. To reduce the GHG emissions in the Transportation and Warehousing sector, the utilization of biofuels and electric automobile will be key measures. According to the analysis in Section 3.1, the Agriculture and Forestry sector, Electric Power Generation, Transmission and Distribution sector, Construction sector and Household Consumption sector all rank at the top for GHG emissions in Saskatchewan. Taking their close mutualism emissions relationship into consideration, it is vital to realize an emissions reduction in these four sectors.

A competition relationship means both sectors are harmed by the relationship in the traditional ecological network analysis. However, the competition relationship reflects good interactions in a GHG emissions flow analysis. According to Table 3, more than half of the competition relationships (i.e. six of eleven) happen in the Natural Gas Extraction sector, including Petroleum and Coal Products Manufacturing sector, Other Manufacturing sector, Wholesale Trade and Retail Trade sector, Transportation and Warehousing sector, Services sector, and Household Consumption sector. These competition relationships show that with more interactions among the above six industries with the Natural Gas Extraction sector, the less GHG emissions will be produced. The results further illustrate that the utilization of natural gas will effectively reduce total GHG emissions. In addition, natural gas fired electricity generation makes up only thirty percent of the total generating capacity in the Province of Saskatchewan, leading to the exploitation emissions relationship of the Natural Gas Extraction sector and the Electric Power Generation, Transmission and Distribution sector. It is expected that the conversion of coal-fired electric power generation to natural gas-fired electric power generation in the future will reduce GHG emissions effectively.

In the comparison of the different scenarios, evident changes for certain sectors can be found. In each column, there are significant differences among the four emission sources. For example, by comparing Fig. 5(a), (e), (i), and (m), it can be seen that the Electric Power Generation, Transmission and Distribution sector plays different role in different scenarios. In Fig. 5(i), the Electric Power Generation, Transmission and Distribution sector is seriously exploited by other sectors. While, in other scenarios, variations of the relationship or the degrees of the relationship can be clearly observed. It's also worth noting that the variations in each row happen in different industries. For instance, the role of Crude Oil Extraction sector varies greatly when comparing Fig. 5(a), (b), and (c). The Crude Oil Extraction sector is exploited by other sectors in the CH_4, and N_2O emission flows, while it exploits some sectors in the CO_2 emissions network. From a systems perspective, Table 2 shows the differences of the twenty scenarios quantitatively. In scenario (o), there are twenty-seven mutualism relationships and twelve competition relationships, while there are only fifteen mutualism relationships and nine competition relationships in scenario (r).

Overall, the mutualism relationship reveals effective pathways to mitigate GHG emissions and the competition relationship reflects good interactions in the GHG emissions flows. The emissions relationships of various sectors are not all consistent with the economic structure. Thus, GHG emissions reduction regulations for specific industries should be done on the strength of a scientific emissions relationship analysis. In the Province of Saskatchewan, there is a need to improve the overall system, and vital to realize emissions reduction in the Agriculture and Forestry sector, Electric Power Generation, Transmission and

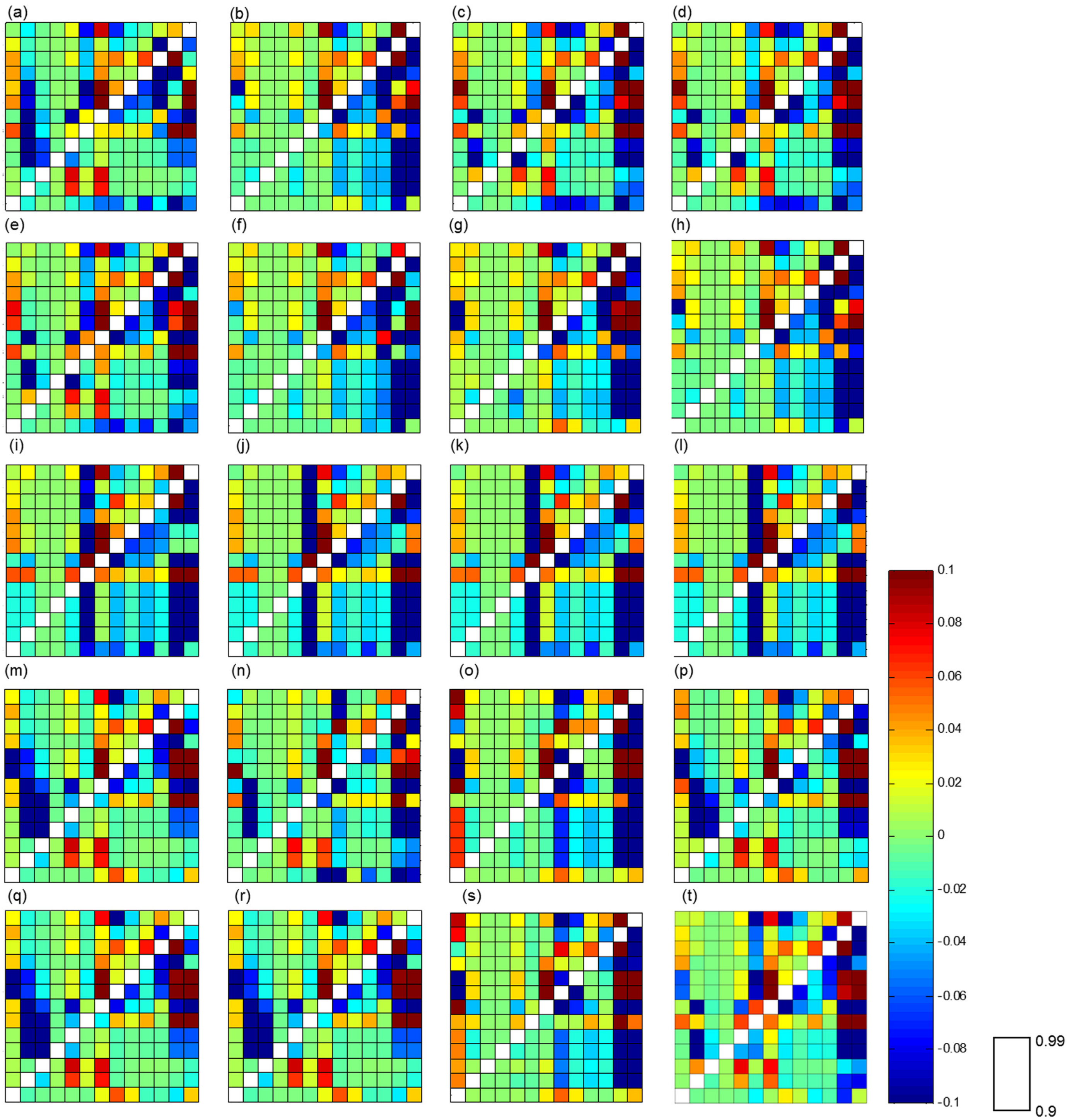

Fig. 5. Emission relationships of thirteen sectors. Notes: The sequence of sectors (from left to right and from bottom to top) in the figure is: AGR, CRU, GAS, COL, MIN, ELE, CON, OIL, MFR, TRD, TRN, SER, C.

Distribution sector, Construction sector and Household Consumption sector. The conversion of coal-fired electric power generation to natural gas-fired electric power generation in the future is expected to reduce the GHG emissions effectively.

4. Conclusions

In this study, a disaggregated ecologically-extended input-output (DECEIO) model has been developed to investigate the integrated GHG emissions and emission relationships of various industries to support the formulation of industrial based legislation in various countries, provinces, and regions. The DECEIO model has been applied to the Province of Saskatchewan, Canada, to illustrate potential benefits and provide a scientific basis for the provincial government in terms of industrial GHG mitigation policy-making. The I-O table has been transformed, aggregated, and disaggregated to fit the GHG emissions satellite factors. The direct and indirect emissions, EEE, EEI, and EEB from four emission sources have been calculated. Emission relationships for thirteen sectors have been developed and analyzed. In addition, a disaggregated analysis that contains different GHG types and

Table 3
The emission relationships of thirteen sectors in scenario (t).

Sector	Mutualism	Exploitation	Control	Competition
AGR	3	6	2	2
MIN	1	9	1	2
COL	1	9	1	2
GAS	1	0	6	6
CRU	1	7	4	1
OIL	1	5	6	1
ELE	2	1	10	0
CON	4	9	0	0
MFR	1	4	7	1
TRN	2	2	8	1
TRD	1	4	6	2
SER	1	5	6	1
C	2	3	7	1

GHG emission sources has been conducted to further investigate potential GHG emissions reduction pathways.

It was found that all emission sources and GHG types should be considered to comprehensively identify the characteristics of emissions flows in the socio-economic system. Production activities for a primary industry are more likely result in direct GHG emissions, while indirect GHG emissions are most likely to occur in secondary and tertiary industries. The type of GHG emissions is more closely related with the EET, while both GHG type and emission source have great impacts on the total emissions and the emission relationships. The emission relationships for various sectors are not all consistent with the economic structure. The competition relationship reflects good interactions in the GHG emission flows and the mutualism relationship reveals effective pathways to mitigate carbon emissions of two sectors simultaneously.

In the Province of Saskatchewan, the Agriculture and Forestry sector, Crude Oil Extraction sector, and Electric Power Generation, Transmission and Distribution sector result in more direct GHG emissions, while the Services sector, Construction sector, and Household Consumption sector emit more indirect GHG emissions. The net emissions embodied in trade for Saskatchewan is exported to other regions, which further indicates that a consumption-based emission reduction responsibility system will benefit the province. Exploitation relationships dominated the system in all of the scenarios. Since the Agriculture and Forestry sector, Electric Power Generation, Transmission and Distribution sector, Construction sector and Household Consumption sector all rank at the top for GHG emissions and their relationships are mutualistic, it is vital to realize emissions reduction in these four sectors. Emission reduction regulations on the Crude Oil Extraction sector, Agriculture and Forestry sector, and Other Mining and Quarrying sector will have significant impacts on Saskatchewan's economy, since the cost increase will reduce their competitiveness in the national or international commodity market. Specifically, clean coal-fired electric power generation, conversion of coal-fired electric power generation to natural gas-fired electric power generation, and renewable energy power generation are the key issues to reduce the CO_2 emissions in the Electric Power Generation, Transmission and Distribution sector. To guarantee the utilization of renewable energy power, energy storage technologies and electricity grid modernization should be further improved with the support from research and development activities. For the Agriculture and Forestry sector, clean natural gas combustion technology and renewable energy utilization technologies should be applied to reduce GHG emissions. Considering the abundant agricultural resources, biomass utilization should be emphasized in the future. Regulations on flaring CH_4 emissions should be considered in the Crude Oil Extraction sector to reduce the total GHG emissions. Meanwhile, supportive policies, such as government investment and clean technology funding, should be implemented to reduce the economic risks by reducing GHG emissions, especially for industries with net positive EEB.

Some limitations will be addressed in future research. First, a computable general equilibrium model based on this study will be developed and applied to simulate the impacts of specific industrial legislations. Second, a stochastic analysis will be introduced in future work to reflect the inherent uncertainties of the data and the calculation process.

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